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Waste heat recovery through plate heat exchanger based thermoelectric generator system

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HIGHLIGHTS

- The HE-TEG system can realize low grade waste heat recovery by heat exchange and thermoelectric power generation.
- The heat exchange efficiency of the metal foam-filled plate heat exchanger is tested as 83.56%.
- Several methods have been proposed to improve TEG output.

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ABSTRACT

A new type of open-cell metal foam-filled plate heat exchanger based thermoelectric generator system (HE-TEG) is proposed to utilize low grade waste heat. This system can realize waste heat recovery through heat exchange and thermoelectric (TE) power generation. An experimental prototype is constructed to demonstrate the feasibility. High heat exchange efficiency of 83.56% between heated air and cold water is achieved. The maximum open circuit voltage of 16 TE couple is 108.1 mV. Several improving methods have been proposed and experimented, including adjustment of the cold water flow rate, enhancement of the heated air inlet temperature and increase of the number of TE couples. The performances of heat exchanger (HE) and thermoelectric generator (TEG) are discussed, respectively.

1. Introduction

Nowadays, energy problems have become worldwide focuses [1]. Several national problems, such as, energy security, energy prices, increasingly competitive global markets and stringent environmental emission regulations, are primary driving forces in the search for efficient, sustainable and economically viable technologies for energy conversion and utilization. The process industries of the chemicals, food and drinks, steels and iron, pulps and paper are substantial energy users, which represent more than 50% of the industrial energy usage [2]. Hendricks and Choate [3] reported that 33% of the manufacturing industrial energy was discharged directly to the atmosphere or cooling systems as waste heat, due to the fact that most industries were incapable of recycling excessive waste heat. Moreover, the global energy demand will increase by almost 35% by 2030 compared with the 2005s level or by up to 95% without the use of energy efficient technologies [2].

Great efforts have been made in improving the energy conversion efficiency, but a considerable amount of energy is still wasted in forms of gas, liquid and solid, which requires large scope of waste energy recovery. The high and intermediate temperature waste can be directly utilized by driving steam turbine and gas turbine to generate electricity, but there are still difficulties in the utilization of waste heat in low-temperature range. TEG technology shows advantages in low grade waste heat recovery [4–8], considering its entire solid state energy conversion mode. Compared with the conventional methods, TEG technology has no moving parts, and it is compact, quiet, highly reliable and environmentally friendly.

The thermoelectric generator applications in the recovery of industrial waste heat have been discussed repeatedly. Chen et al. [9] analyzed the case of integrating TEG into thermal energy systems, especially heat exchangers and cooling systems of the combined heat and power production. Dan et al. [10] proposed a liquid metal based TEG system which served to harvest waste heat with the efficiency of 2%. Gou et al. [11] presented suggestions to enhance the TEG performance, such as increasing the waste heat temperature, expanding heat sink surface area in proper range and enhancing cold-side heat transfer capacity. As the source that

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Nomenclature

Abbreviation
- HE heat exchanger
- HE-TEG heat exchanger based thermoelectric generator
- TE thermoelectric
- TEG thermoelectric generator

Symbols
- c_p specific heat capacity (kJ/(kg K))
- P pumping power
- PPI pores per inch
- q_m mass flow rate (kg h^{-1})
- q_v volume flow rate (m^3/h)
- T temperature (°C)

Greek symbols
- Δp pressure drop (Pa)
- η heat exchange efficiency
- ϕ actual heat flux (W)
- ϕ_{max} maximum heat flux (W)

Subscript
- c cold water
- h heated air
- in inlet
- out outlet

TEG utilizes is low grade waste heat, cheap or free, and there is no consume of fresh fuel for electricity production, it will be able to obtain additional benefits in terms of an improved overall efficiency. In addition, the energy conversion efficiency is quite attractive when the TEG works in a parasitic mode.

Most of TEG applications in waste heat recovery involved in effective heat exchangers [6,12,13]. In terms of heat transfer enhancement, filling metal foams in the flow channel is an attractive method. According to the research of Lu et al. [14], the heat transfer rate was enhanced by more than 15 times by inserting the metal foams in the flow channel. Mahjoob and Vafai [15] showed that inserting metal foams in the double pipe heat exchanger can significantly increase heat transfer rate at the expense of increased pressure drop. Recently, it is proposed to use metal foam heat exchanger instead of the air-cooled finned heat exchanger [16] and the conventional finned-tube heat exchanger [17]. Hsien et al. [18] experimentally studied the heat transfer characteristics of several heat sinks made of metal foams with different porosity (0.87–0.96) and PPI (10–40). Mancin et al. [19] conducted a series of experiments testing four foam samples with 5, 10, 20, and 40 PPI and the similar porosity (0.905–0.934), and they found that the pressure drop decreased as the number of pores per inch decreased from 40 PPT to 5 PPI.

The experiments in most of the reports used commercial thermoelectric modules which were mounted and utilized in a cross-plane way. However, when TE modules were sandwiched between hot and cold side, the low thermal conductivity of TE modules would block the heat exchange process. In this paper, a new type of metal foam-filled heat exchanger based thermoelectric generator system is proposed. Different from the conventional cross-plane conditions, this kind of heat exchanger is able to generate available temperature difference between cold and hot layers in an in-plane way. This system can realize waste heat recovery by combining heat exchange and TE power generation.

2. Experimental setup

Waste heat flow path of the HE-TEG system for low temperature waste heat recovery is as follows: Power generation works as a parasitic mode which is attached to heat exchanging process. The majority of waste heat is captured by the process of heating water. A portion of the waste heat flux is converted into electricity by TEG as by-product. In terms of heat exchange process, some waste heat dissipates into the surroundings through heat exchanger walls. In the end, the remaining waste heat is directly discharged into the atmosphere along with exhaust gas.

The schematic diagram of the HE-TEG system is shown in Fig. 1. This system consists of HE-TEG unit, air supply and heating unit, cold water channel and data acquisition system. Waste heat is simulated by heated air. The air is supplied by an air compressor, and then it flows through a spiral steel pipe, rapped by resistance wire, whose output power is controlled by a voltage transformer. Cold water is used as waste heat capturing fluid. Back pressure valve is mounted to control the air pressure (0.2 MPa). Globe valve and rotor flow meters are adopted to control the flow rate of heated air and cold water.

HE-TEG unit is shown schematically in Fig. 2. It is comprised of a multi-layer compact metal foam-filled plate heat exchanger and TE couples. The dimension of the assembled HE is 200 mm × 79 mm × 79 mm. Steel plates with thickness of 1 mm are used for heat exchanging mediums between cold water and heated air. Side surfaces, where TE couples are pasted, are made of steel plate either. Square steels with dimension of 12 mm × 12 mm × 12 mm are placed at corners of the heat exchanger as upholders for the flow channel. Between every two steel plates, open-cell nickel metal foams (10 PPI, porosity of 0.96) are filled in the flow channel as heat transfer enhancement mediums and assistant support materials. Cold water and heated air flow in the opposite direction as approximate counter flow. As illustrated in Fig. 2, inlet and outlet of cold fluid are set along the length direction, and in terms of the hot fluid they are set at different end of the side surface. To prevent heat loss, the HE-TEG unit is wrapped by thermally insulated ceramic fiber cloth.

Considering the special application of TE modules in the HE side surface, TE couples are self-constructed by Bi_2Te_3-based rectangle thermoelectric materials. The Seebeck coefficient, electrical conductivity and thermal conductivity are 2.18×10^{-4} V K^{-1}, 1.175×10^5 S m^{-1}, 1.7 W K^{-1} m^{-1} for P-type TE materials and -2.15×10^{-4} V K^{-1}, 1.225×10^5 S m^{-1}, 1.9 W K^{-1} m^{-1} for N-type TE materials, respectively. Each couple consists of one P-type TE leg and one N-type TE leg with the dimension of 1 mm × 1 mm × 14 mm. The TE leg is constructed by 4 small rectangle blocks (1 mm × 1 mm × 3.5 mm), which are connected by conductive silver paste. TE couples are pasted to the back of thermally conductive and electrically insulating polyimide tapes with conductive silver paste, then the polyimide tapes are adhered to the HE side surfaces with the sticky side. In order to study the performance of TE power generation, different numbers of TE couples (1, 2, 4, 8 and 16) are integrated to the HE.

Pressure drop of heated air and cold water is measured by differential manometers. K-type thermal couples are used to measure temperatures of heated air and cold water. In addition, Pt100 sensors are mounted on middle two layers to measure side surface temperature difference. Finally, all the temperature, voltage and

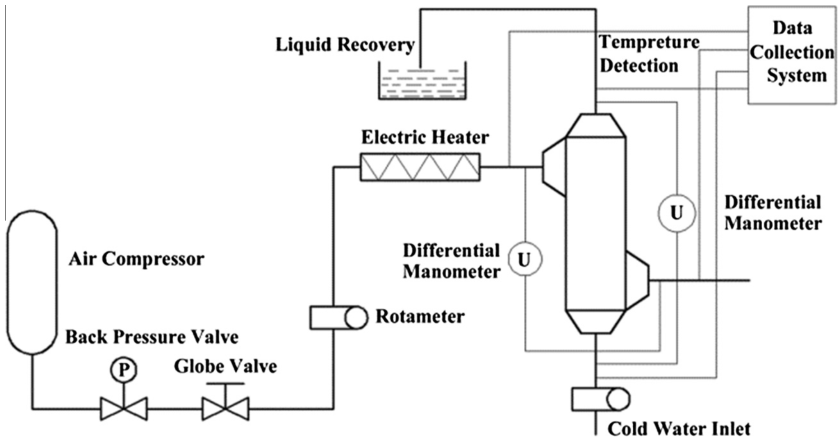

Fig. 1. Schematic of HE-TEG system for waste heat recovery.

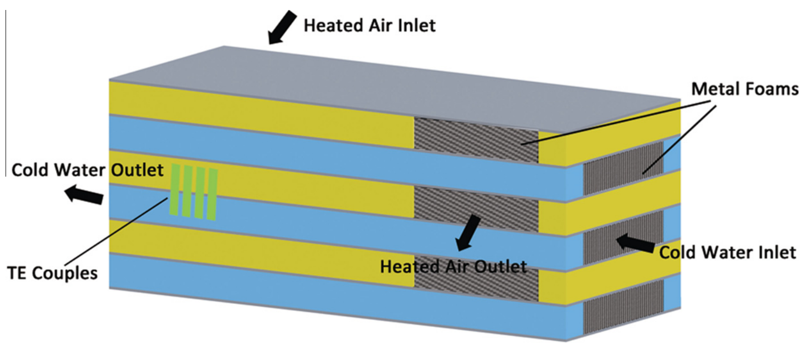

Fig. 2. Schematic of the HE-TEG unit structure.

electrical resistance values are collected by data acquisition system (Agilent 34970A).

3. Results and discussion

For the experiment testing, the data is measured at the heated air and cold water temperature of 163 °C and 19 °C, and corresponding mass flow rate of 8.52 kg h^{-1} and 8 kg h^{-1}.

3.1. Performance of HE

The fluid temperature changes of air-inlet, air-outlet, water-inlet and water-outlet with the operation time are shown in Fig. 3. The experiment starts with turning on of the air electrical heater. It is observed that the fluid temperature changes regularly with the operation time. The air inlet temperature firstly rises with operating time going by, which results in the corresponding increase of air outlet and water outlet temperature. In less than 900 s, the air-inlet, air-outlet, water-inlet and water-outlet temperatures will come to the steady state of 163 °C, 42 °C, 19 °C and 46 °C, respectively. It is demonstrated that the prototype system is fast enough to reach the long-term stable working conditions.

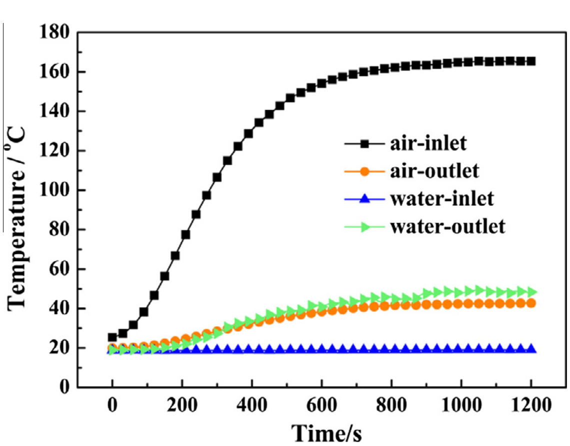

Fig. 3. Temperature changes of air-inlet, air-outlet, water-inlet and water-outlet as a function of time.

The heat exchanging performance of the HE is evaluated by heat exchange efficiency (η), which is described as:

$$\eta = \phi/\phi_{max} \tag{1}$$

where ϕ is the actual heat flux that cold water captures, ϕ_{max} is the maximum heat flux that heated air can supply. ϕ and ϕ_{max} are given by:

$$\phi = q_{mc}c_{pc}(T_{c,out} - T_{c,in}) \tag{2}$$

$$\phi_{max} = q_{mh}c_{ph}(T_{h,in} - T_{c,in}) \tag{3}$$

where q_{mc}, c_{pc}, $T_{c,in}$ and $T_{c,out}$ are mass flow rate, specific heat capacity, inlet and outlet temperature of cold water, respectively. q_{mh}, c_{ph}, and $T_{h,in}$ are mass flow rate, specific heat capacity and inlet temperature of the heated air, respectively. The heat exchange efficiency is calculated as 83.56%, indicating very high heat exchange ability. This is mostly due to the heat transfer enhancement by filling open-cell metal foams in the flow channel. The rate of heat transfer is enhanced by conducting the heat to the metal foam frames, which have a large accessible surface area per unit volume, along with high interaction with the fluid flowing through them. The high

heat exchange efficiency will promote the waste heat recovery performance.

Pumping power is another factor of the HE performance. In the case of waste heat recovery, the consumption of pumping power is expected to be lower at the similar heat exchange ability. It is defined as the product of the pressure drop and the volume flow rate:

$$P = \Delta p \cdot q_v \tag{4}$$

where P is pumping power, Δp is pressure drop and q_v is volume flow rate of the fluid through the heat exchanger.

The variations of the heated air and cold water pressure drop with the mass flow rate are shown in Fig. 4. As can be seen, pressure drop increases with the mass flow rate of both heated air and cold water enlarging. At the working conditions, the pressure drop of heated air (931.6 Pa) is larger than that of cold water (9.8 Pa). The total pumping power is calculated as 0.84 W, which is much lower than the recycled waste heat that is captured by cold water (285.3 W). This is due to the adoption of the metal foams of small pore density (10 PPI) and high porosity (0.96). Small pore density means large pore diameter and high porosity means more flowing space for the fluid. All these factors account for the decreasing pressure loss of heat exchanging in waste heat recovery process. Furthermore, considering the high waste heat recovery ability of the metal foam-filled heat exchanger, the pressure drop will not be a big problem.

3.2. Performance of TEG

According to the Seebeck effect, temperature difference is crucial to the performance of TEG. In order to find a suitable place for TE couples, the temperature difference between two adjacent layers at the region near heated air inlet and outlet are measured, respectively. Fig. 5 shows the comparison of surface temperature difference of middle two adjacent layers. It can be seen that both the air inlet and outlet temperature difference climb with air inlet temperature. Furthermore, the temperature difference at air inlet surface is larger than that at air outlet surface. It is because the cold water temperature rise range is smaller than the heated air temperature decline range, thus, the temperature difference of heated air inlet and cold water outlet is larger than that of the heated air outlet and cold water inlet. So, when it comes to the side surface temperature difference, the region near heated air inlet is higher than that near heated air outlet.

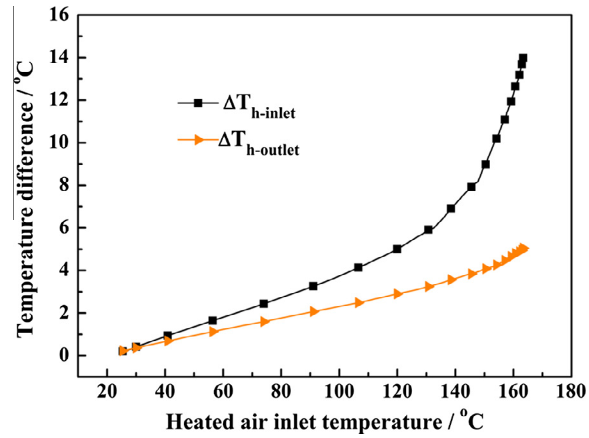

Fig. 5. Comparison of side surface temperature difference of middle two adjacent layers.

With the changes of working conditions, the side surface temperature difference of middle two adjacent layers near the heated air inlet is supposed to be different. Here, heated air mass flow rate is fixed, while cold water mass flow rate changes from 5 kg h^{-1} to 40 kg h^{-1} and heated air inlet temperature alters from 92 °C to 198 °C. The changes of temperature difference with cold water flow rate are shown in Fig. 6. With the increasing of cold water flow rate, it can be seen that the temperature difference climbs up firstly and achieves the maximum value of 13.8 °C at 8 kg h^{-1}, after then it gradually goes down to 6.3 °C at 40 kg h^{-1}. The flow rate of cold water influences the temperature difference of two adjacent layers to a great extent, since changing cold water mass flow rate will affect the temperature distribution of both the heated air and cold water. Excessive cold water makes the heated air to be cooled to a very low temperature. However, insufficient cold water results in the sharp rise of cold water outlet temperature. The two factors will decrease the temperature difference. The cold water mass flow rate of 8 kg h^{-1} comes out to be the optimal point for achieving the maximum side surface temperature difference near the heated air inlet.

Fig. 6 illustrates the changes of temperature difference with increasing of heated air inlet temperature as well. As is shown in this figure, increasing heated air inlet temperature will enlarge the temperature difference between two adjacent layers, which

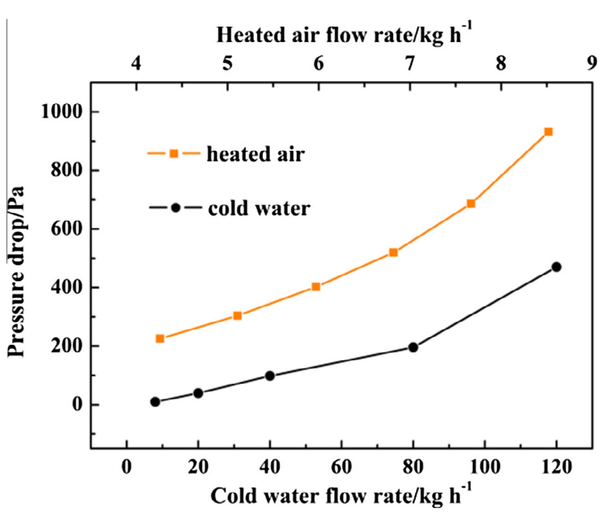

Fig. 4. Variation of pressure drop with the mass flow rate of cold water and heated air.

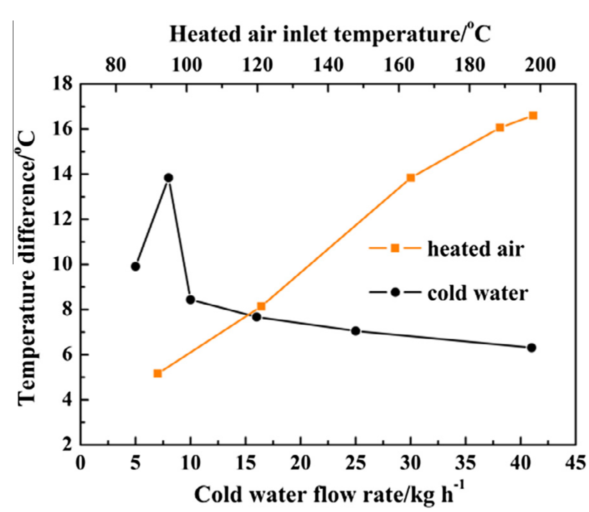

Fig. 6. Changes of temperature difference with cold water flow rate and heated air inlet temperature.

demonstrates the feasibility of enhancing the TEG output by increasing the heated air inlet temperature. However, considering the long-term tolerance of the experimental prototype, air is generally heated to 163 °C in the experiment.

A series of open circuit voltage values of one TE couple changing with temperature difference are shown in Fig. 7. As the temperature difference varies from 0 to 13.8 °C continuously, the open circuit voltage values climb approximately linearly from 0 to 5.5 mV. The trends of temperature difference indicate that each addition of 1 °C temperature difference results in 0.4 mV addition of open circuit voltage. The approximate Seebeck coefficient of the assembled TE couples is calculated as 4×10^{-4} V K^{-1}, which is slightly less than the sum of P-type and N-type thermoelectric materials, due to the influence of jointing materials.

The maximum power output of one TE couple is obtained when load resistance is equal to internal resistance (here 2.6 Ω). As a consequence, it is convenient to calculate a series of maximum power output values changing with temperature difference based on the voltages. The power output of one TE couple is shown in Fig. 7 as well. It illustrates the output power increases in a quasi-exponential trend with temperature difference. Thus, increasing the temperature difference will distinctly promote the output power.

The open circuit voltage of 2, 4, 8 and 16 TE couples are also measured to predict the TEG performance of more TE couples. Fig. 8 illustrates the comparison of the open circuit voltage of different number of TE couples. With the operating time going by, all the open circuit voltage values increase continuously to a relatively stable level around maximum values and keep steady afterwards. As illustrated in the figure, by increasing the number of TE couples from 1 to 16, the maximum open circuit voltage goes up approximately linearly from 5.5 mV to 108.1 mV. It demonstrates the feasibility of increasing the number of TE couples to enlarge the electricity generating capacity.

The numbers of TE couple are essential for the performance of TEG. Currently, the commercial TE modules commonly consisted of hundreds of TE couples and were utilized in a cross-plane mode. Unlike the conventional TE modules, the in-plane mode of the HE-TEG system enables the combination of efficient heat exchange and power generation. Here, the porous metal foams can significantly promote the waste heat recovery through enhancing the heat transfer rate, which is resulted from the large accessible surface area per unit volume, along with high interaction with fluid flowing through the metal foams. For this reason, the low power generation capacity of the in-plane mode is acceptable. Moreover, in terms of the experimental prototype, only a small portion of the side surface was exploited, which indicates the feasibility of installing more TE couples. In the case of several hundred TE couples, the theoretical open circuit voltage of the experimental prototype is evaluated to be much larger. Furthermore, in the industrial application case of thousands of TE couples, the power generation will be applicable.

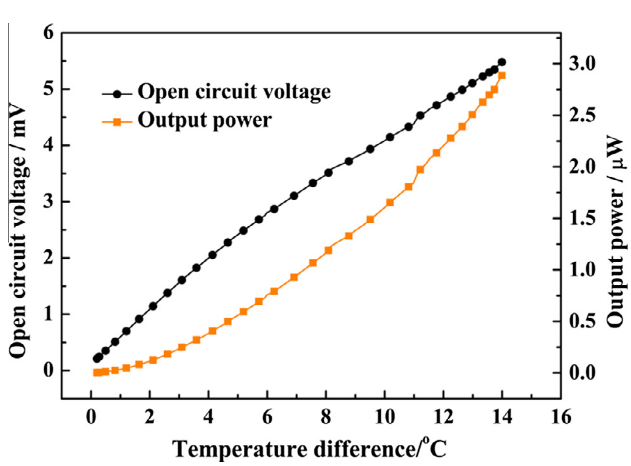

Fig. 7. Variation of the open circuit voltage and output power as a function of temperature difference.

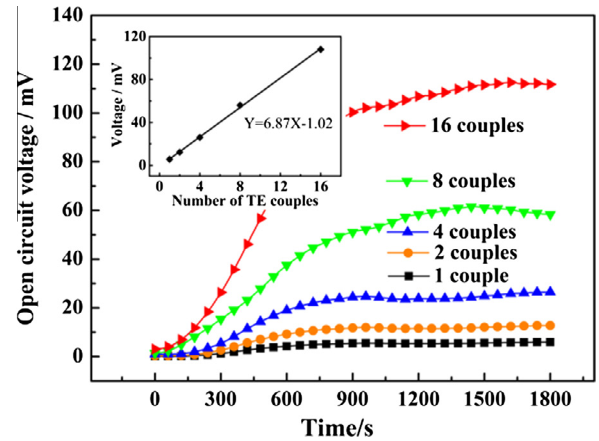

Fig. 8. Comparison of the open circuit voltage of 1, 2, 4, 8 and 16 TE couples.

4. Conclusions

In this paper, a set of HE-TEG system are constructed and tested for low-temperature waste heat recovery. The performances of HE and TEG units are discussed separately. At the experimental working conditions, heat exchange efficiency between heated air and cold water is 83.56%. The metal foams play an important role in enhancing the heat transfer process. The maximum temperature difference between two adjacent layers is 13.8 °C and the maximum open circuit voltage of 16 TE couple is 108.1 mV. By increasing the numbers of TE couples, the open circuit voltage is enlarged linearly. Further experiments and CFD simulation are still in progress to conduct a system level optimization.

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